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13. ABSTRACT (Maximum 200 words)

The primary goal of this MURI was to develop a superior meso-scale piezoelectric actuator device when compared to conventional smart actuation systems. The secondary goal was to evaluate the potential use of the device in rotorcraft systems to alter fluid-structure interactions and to decrease vibration loads and/or alleviate dynamic stall. The piezoelectric activated device utilized frequency rectification concepts along with single crystal silicon micro-machined gears to produce step-like motions amplifying the displacement output of conventional piezoelectric stacks from microns to millimeters. The order of magnitude displacement improvement was also reflected in an order of magnitude increased power output of the system when operated in structural systems such as the rotorcraft. Accomplishing this goal required several fundamental science and engineering questions to be addressed. These included but were not limited to the long term electro-mechanical fatigue of piezoelectrics, the intrinsic strength of single crystal MEMS components, meso-scale manufacturing concepts, and development of thin film lithium batteries. In regards to rotorcraft applications, experimental and analytical studies indicated substantial reductions in vibrations up to 90% along with alleviation of dynamic stall.

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I. Abstract

The primary goal of this MURI was to develop a superior meso-scale piezoelectric actuator device when compared to conventional smart actuation systems. The secondary goals was to evaluate the potential use of the device in rotorcraft systems to alter fluid-structure interactions and to decrease vibration loads and/or alleviate dynamic stall. The piezoelectric activated device utilized frequency rectification concepts along with single crystal silicon micro-machined gears to produce step-like motions amplifying the displacement output of conventional piezoelectric stacks from microns to millimeters. The order of magnitude displacement improvement was also reflected in an order of magnitude increased power output of the system when operated in structural systems such as the rotorcraft. Accomplishing this goal required several fundamental science and engineering questions to be addressed. These included but were not limited to the long term electro-mechanical fatigue of piezoelectrics, the intrinsic strength of single crystal MEMS components, meso-scale manufacturing concepts, and development of thin film lithium batteries. In regards to rotorcraft applications, experimental and analytical studies indicated substantial reductions in vibrations up to 90% along with alleviation of dynamic stall.

II. Statement of Problem Studied

Prior to this program, piezoelectrics were limited in displacement output, typically on the order of microns. Previous attempts to remedy this problem included displacement amplification techniques that led to corresponding reduction in force outputs. While successful, these approaches do not improve the overall power density of the piezoelectric actuator thereby limiting its usefulness. During this MURI program we proposed and implemented a frequency rectification approach to increase the displacements by reducing frequency output rather than force output. Since piezoelectrics operate in the kHz regime and the structural community requires operation in the 1-100 Hz regime frequency rectification is both acceptable and desirable. Therefore, rectifying the frequency from 1000 Hz to 100 Hz will increase the power output of a piezoelectric actuator by one order of magnitude. Based on the research findings made during this program on this concept, DARPA initiated a Compact Hybrid Actuator Program to design, fabricate, and test various frequency rectification devices. A device similar to the one developed under this MURI is now being commercialized by Burleigh Instruments, the original developer of piezoelectric inchworm motors.

Developing a successful piezoelectric frequency rectification device required collaboration between material scientists, mechanical engineers, and designers. Fabrication of small gearing mechanisms, on the order of microns, transferred macroscopic mechanical load in the device. Both developing manufacturing approaches and assessing strength of these microcomponents was a challenging task with relatively little research available in the open literature. In addition to fabricating small components, the operation of the piezoelectric ceramic at high fields and large stresses over millions of cycles is not understood. Finally, integrating micro-based components into a macro/meso-structure poses significant manufacturing challenges to operating a frequency rectification device.

The frequency recitification device developed under this program was called the meso-scale actuator device (MAD). We investigated applications to three specific rotorcraft problems, vibration reduction, blade vortex interaction, and dynamic stall. Both the vibration reduction problem and blade vortex interaction problem were studied analytically using an active flap on the blades of the rotorcraft. Potentially, the MAD device could control these active control flaps. To investigate dynamic stall, we experimentally investigated flow control concepts near the leading edge of the rotorblade. During this study, we discovered that up to 90% of the vibrations can be reduced with the active control flap and dynamic stall can be significantly delayed using flow control concepts.

In general, this program developed a piezoelectric frequency rectification device (MAD) that integrated micro-machined components and piezoelectrics into a device far superior to its individual components. The palm size device (characteristic dimension on the order of 100mm) could produce up to 100 lb output force with motion speeds up to 10 mm/s. These properties represent an order of magnitude improvement over existing piezoelectric stack actuation systems and relies on the frequency rectification concept. The palm-size device was investigated for potential use in rotorcraft systems with significant reductions in vibrations or alleviation of dynamic stall reported. During this project a number of scientific advancements were made that are not detailed in this report. For detailed information on each research area, the reader is referred to the more complete descriptions provided in the published papers listed in section IV.

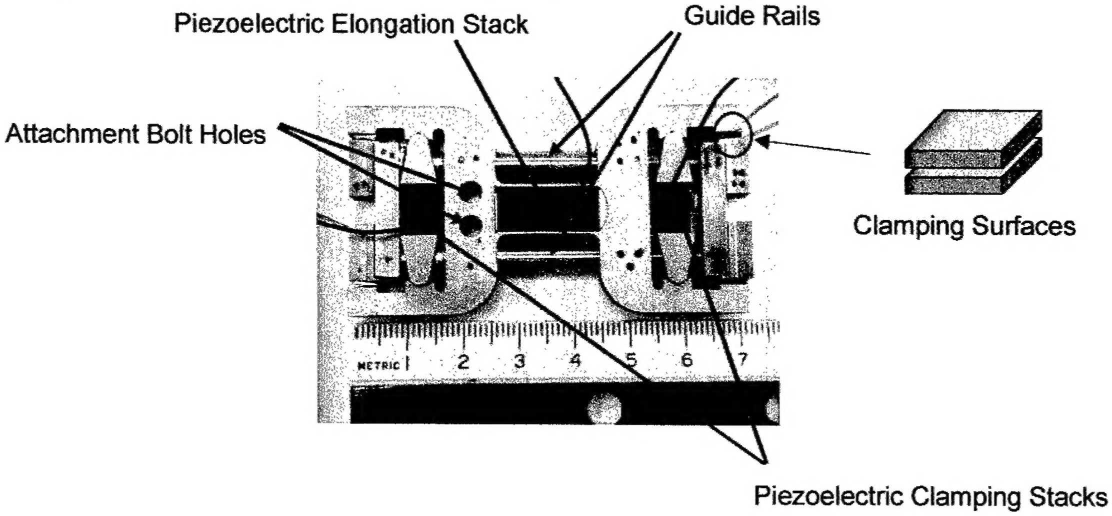
III. Summary of Important Results

Meso-Scale Actuator Device (MAD:

1. Demonstrated that MEMS microridges fabricated on separate wafers could be engaged and disengaged using a piezoelectric drive actuator. This work established that MEMS components combined with active materials (piezoelectric) provide new approaches for developing actuation systems with characteristics far superior to conventional ones.
2. Demonstrated that MEMS microridges combined with a piezoelectric stack can be used to produce a step-like motion (i.e., frequency rectification) increasing the overall displacement output from microns to millimeters, an order of magnitude larger than the stand alone stack. This work confirms that tolerances associated with microscopic components, while challenging, does not represent a fundamental obstacle for producing hybrid actuator systems.
3. Experimentally synchronized the mechanical interlocking of microcomponents at frequencies on the order of one kilohertz. For the helicopter application, which is the focus of this research, the power produced by the MAD system operated at one kilohertz was one order of magnitude larger than conventional piezoelectric stacks.
4. Demonstrated that microcomponents can transfer macroscopic loads, a first for the scientific community. A silicon chip containing ridges on the order of 5 microns supported mechanical loads well over 200 N. This fundamental work opened the door to new applications for microcomponents that one day may replace conventional gearing mechanisms in everything from mechanical watches to automobiles. However, these results also indicate that a large

void exists in available scientific data regarding the strength/fatigue of microcomponents. Our experimental results support this contention and also suggest geometry, material, and manufacturing processes play a prominent role in dictating the overall strength.

5. Designed/fabricated and tested a prototype meso-scale actuator device (MAD) supporting 500 N load moving at 10 mm/s (i.e. 1000 Hz) with displacements approaching a millimeter (see Figure 1). Therefore, the new actuator represents a remarkable improvement over existing systems. While the results were very promising, we would like to note that damage to the ridges during walking and the constraint of the step size are limiting features of the device. If the ridges could be fabricated from tougher materials (we also examined other materials) and the step size could be variable the device would be ideal for many structural applications including those that require precision control.



Strength of Micro-Components:

1. Designed new tests to characterize strength/fatigue of microcomponents. This effort included designing and fabricating an innovative micro-scale dog-bone specimen similar to ASTM standards required for evaluating macroscopic material systems. In regards to the micro-scale dog-bone specimens, several different materials manufactured with different processes were evaluated. Initial results indicate that manufacturing processes prominently influence the strength (i.e. over 100%) of a microcomponent.
2. Measuring the strain response of the micro-structures is difficult. To overcome this problem, a laser interferometric system was constructed to monitor surface deflections on the specimen. The system provides submicron resolution at loading frequencies that approach 100 Hz. Currently this system is being used to measure surface strains during tensile loading.

Piezoelectric Materials:

1. Piezoelectric materials are the most plausible candidates for use in the meso-scale actuator device. However, the actuator will be operated at large frequencies (i.e. kHz) for long periods with a total life approaching 5000 hours (rotorcraft requirement). The long term cycling of piezoelectric materials under combined mechanical and electrical loading has

never been studied by the scientific community and thus poses a serious obstacle to the smart materials community. While a few researchers have investigated electric fatigue, they did not study electro-mechanical fatigue. We have found that electro-mechanical fatigue is a truly complicated problem. Our work indicates that actuator piezoceramics, those producing over 2000 (some over 4000) microstrain, fatigue fundamentally different than pure electric fatigue and to a large extent depend upon the material being studied. In the severe nonlinear regime, generally the degradation can be mitigated with the application of compressive mechanical loads and exacerbated with the application of tensile loads. In the quasi-linear regime, the interaction between stresses caused by internal variant electric fields and external mechanical loads is not fully understood at this time, due to the fact that domain reorientation effects are dependent upon both load and electric field levels.

2. Analytically demonstrated that "optimal" piezoelectric properties exist to eliminate stress concentrations around internal anomalies within the material. These optimal properties, which are independent of anomaly geometry and distribution, suggest a universally valid relationship. Recognizing these relationships will pave the way for developing new piezoelectric materials, we proposed a new approach not previously considered by the scientific community to eliminate fatigue, i.e. tailoring the coefficients without reducing the strain output. This finding represents a scientific discovery that has significant ramifications for future piezoelectric materials such as the new single crystal piezoelectrics.
3. Evaluated internal strain distributions during domain evolution with a laser inteferometric technique to understand the fatigue process. This study was the first that used Moire Inteferometry, a full field strain measurement technique, to measure the distribution of strains between dissimilar domain structures. Results indicate that dissimilar domains produce considerably larger internal strain/stresses than previously thought. These results have significant implications regarding the long-term fatigue of new single crystal piezoelectric materials, which undergo a phase change, producing two dissimilar structures within the material. Our results indicate that these two structures are a key factor that causes fatigue degradation of this class of ferroelectric materials. By understanding this phenomenon, we believe that it can be overcome. One approach being investigated is applying external mechanical loads to mitigate the internal stress concentrations and/or adjusting material properties (see 2 above).
4. Developed a nonlinear finite element code to understand the internal stress distribution in piezoelectric ceramics undergoing phase transformations, including domain wall motion. While a handful of these nonlinear models are currently being developed, the UCLA model is the only one (we are aware of) that has been validated with experimental results generated from full field measurements, i.e. the Moire system. Current results are truly promising; however, they also indicate that modeling the nonlinear behavior of piezoelectric actuators is still in its infancy. Once again these models represent a critical component in understanding the response of current and proposed piezoelectric actuators.
5. Initiated a collaborative study with Rockwell Science Center to investigate some novel piezoelectric materials including PLZT and new single crystal piezoelectric materials. Test results on the Rockwell PLZT composition revealed a behavior not previously observed with other piezoelectric materials. When a compressive stress is applied to this material, instead of the typical displacement degradation, the PLZT materials response improved. We suggest that this improvement is the result of domain wall motion initiated by the compressive stress that is subsequently reactivated when the electric field is applied, thereby amplifying the

with a decrease in cell capacity.

Blade Manufacturing:

1. Designed and fabricated a Wortmann FX-098 composite blade for wind tunnel testing. In addition to this blade several other geometries were manufactured using Laminated Object Manufacturing to permit quick and easy verification of actuator/sensor positioning within a typical blade design. The span-wise uniformity, a critical requirement, measured by an X-Y-Z measurement probe station was found to be very consistent. Without this component of research in the program it would be difficult to conduct a collaborative study on issues ranging from actuator development to rotorcraft applications. The blade provided the opportunity to quickly evaluate and test both the research concepts and actuator designs. In one sense, this portion of the program provides the vehicle for conducing collaborative studies amongst the various researchers.

Experimental Dynamic Stall Alleviation:

1. Using the blade system manufactured, experimental tests were conducted to understand the stall phenomena associated with rotorcraft systems in an effort to delay these detrimental phenomena. We implemented several different techniques to alleviate separation effects that lead to wing structure stall. This research has demonstrated that small displacement have beneficial influences on blades operated in the stall regime including dynamic stall.
2. Measured static pressure via 26 pressure sensors integrated into the Wortmann FX-098 wing structure. This data is a critical component to understand and control the separation effects causing the wing structure to stall. The pressure sensors provided less than 5% differences when compared to a validated load cell calculated over the entire angle-of-attack (AOA) operating range.
3. Validated static and unsteady stall characteristics for both the Wortmann FX-098 wing and a previously studied Wortmann FX-137 wing. For the static stall cases, we demonstrated that a small disturbance placed at or near the leading edge could delay stall and eliminate the associated hysteresis. This result suggested that similar results might be possible for the dynamic stall case. In fact recent tests have confirmed that dynamic stall can be alleviated with small surface displacements.
4. The ability to control the dynamic stall problem represented a fundamental scientific issue addressed during this program. Recently, we measured the transient pressure distribution for dynamic stall conditions to gain a better understanding of this phenomenon. Very little, in terms of control work using small structural perturbations, is being done in this area. Successful control techniques that manipulate the unsteady flow characteristics could lead to more general applications of the concepts proposed in this research and possibly real-time control of a rotor-blade.
5. Developing a miniature device that can adjust to the large range of operating conditions encountered in a rotor-blade is also being investigated. The ability of the device to produce substantial reduction of dynamic stall effects is the overall objective of this portion of the research. Here, the existence, strength, growth and convection of the dynamic stall vortex (d-s-v) are of primary importance. Currently, the qualitative features of the d-s-v are present but

displacements capabilities of the actuator. This result is consistent with the domain wall management philosophy that we are implementing to produce piezoelectric materials whose strain output exceeds 4000 microstrain. The principal problem with these large displacement actuators is still fatigue degradation during long term cyclic loading.

6. Evaluated several piezoelctric stacks for increasing the strain output using domain wall concepts. Results indicated that the strain output could be doubled and in some circumstance tripled for appropriate loading conditions. The stacks produces strains on the order of 3500 microstrain compared with manufacturers measured 1000 microstrains. Fatigue tests suggest that the increased domain wall motion leads to quicker degradation than found on stacks operated at "acceptable drive and load levels." This work has guided Boeing rotorcraft to operate the stacks for an upcoming flight test on a rotorcraft incorporating piezoelectric stacks.

Polymer Lithium Battery:

1. Used lithium polymer batteries to power piezoelectric actuators. This work demonstrated that thin film lithium batteries are able to supply ac power for operating multi-layer actuators. Some of the key features of this work are as follows:
   - Lithium polymer batteries were operated in ac mode as compared to standard dc operation. Such ac operation is essential for actuator applications.
   - 6 and 12 Volt battery modules were constructed which operated up to 1000 Hz and exhibited energy densities of 150 to 200 mAh/g
   - The battery modules demonstrated the powering of various piezoelectric stack actuators. A lithium polymer battery was also used to power a piezoelectric actuator patch that was part of a damage detection system.
   - The battery modules are rechargeable and, operating at 100 Hz, as many as 100 discharge/charge cycles were demonstrated
   - A study of cycling behavior showed that loss of battery capacity is a function of frequency over the range 10 to 500 Hz.

2. Developed and characterized battery materials. This work primarily involved studies of the cathode material. The emphasis was on determining how the fundamental properties of the cathode were affected by battery processing and operational conditions.
   - For the cathode material, we selected vanadium oxide aerogels, optimized the processing conditions and developed methods for integrating this material into the battery structure. The material has a reversible lithium capacity in excess of 400 mAh/g, which is three times greater than commercial cathode materials.
   - *In-situ* electrochemical impedance measurements and simulations conclusively showed that the formation of a surface layer leads to an increase in charge transfer resistance at the cathode/electrolyte interface and subsequent capacity loss in the battery.
   - Processing conditions which rigorously avoid moisture exposure were shown to be the key feature in minimizing/avoiding the formation of deleterious surface layers and leading to excellent capacity on cycling.
   - Atomic force microscopy (AFM) was combined with electrochemical characterization methods to observe, in real-time, morphological changes in the cathode during cell discharge/charge. Overdischarge is found to cause irreversible changes in cathode thickness which correlates

some quantitative aspects of the vortex have not yet been validated and will be researched during the final two years.

Rotorcraft Vibration Alleviation Analysis:

1. Developed an unsteady aerodynamic model of airfoil/flap combination modeled using rational function approximation (RFA), which includes compressibility and unsteady free stream effects
2. Combined the unsteady aerodynamic model, with a free wake and a finite element model of the blade structural dynamics, to produce an aeroelastic code simulating vibration reduction in forward flight. This code produced better agreement with experimental data obtained Fulton & Ormiston (AHS Proceedings 1998, pp. 433-451) than any other code available.
4. Demonstrated that vibration reduction due to high-speed forward flight (VRHFF) and vibration alleviation due to BVI (VABVI) represent two fundamentally different problems. In both cases the actively controlled flap produces vibration reduction in excess of 90% from baseline vibration levels. However for BVI alleviation flap deflections and power requirements are 3-4 times higher than those required for vibrations due to high-speed flight.
5. Developed improved vibration control laws in presence of limits on flap deflections, which result in actuator saturation and loss of vibration reduction effectiveness. Saturated flaps only reduces vibratory loads by an average of 30% while the baseline control input produces over a 90% reduction.
6. A new control procedure for limiting flap deflection authority was developed. In this approach the controller adjusts the control-weighting matrix automatically until flap deflections are within the prescribed limits. With a 4 degree limit on flap deflection, an 80% vibration reduction is achieved despite the practical limit imposed on the flap deflections.
7. Aeroelastic scaling laws were developed, which are particularly useful, when dealing with systems where actuation is provided by active materials.

IV. Publications

The research results have been presented and published at a large number of conferences and journals during this program. One of the conference papers submitted in 1996 received the best paper award from the Adaptive Structures and Material System committee of ASME. In addition to the large number of conference and symposium papers, some of which are reviewed, a number of journal articles have either been submitted or accepted by reputable journals. The following provides a list of research published in journal and conference papers during the conduct of this MURI

Journal Publications

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IV. AWARDS AND HONORS

The principal investigators participating on this program have received a number of awards and honors over the MURI program. These include national and international recognition. The following represents an abbreviated version of some of the awards given to our principal investigators during this MURI program.

- Chih-Ming Ho elected to membership in the National Academy of Engineering.
- Chih-Ming Ho Member of Academia Sinica
- Peretz Friedmann recipient of 1996 AIAA Structures, Structural Dynamics and Materials Award.
- Peretz P. Friedmann selected the SDM Lecturer at the 38th AIAA/ASME/ASCE/AHS/ACS SDM conference
- Tom Hahn recipient of Medal of Excellence in Composite Materials from University of Delaware Center for Composite Materials.
- Tom Hahn recipient of Ho-Am Prize in Engineering
- Bruce Dunn named fellow American Ceramics Society.
- Bruce Dunn won Materials Science Award for Outstanding Accomplishment in Metallurgy and Ceramics; Department of Energy (Office of Basic Energy Sciences)
- C.J. Kim recipient of National Science Foundation Career award.

- Greg Carman recipient of best paper award from Adaptive Structures and Material Systems ASME.
- Greg Carman recipient of Northrop-Grumman Young Investigator Award

V. SCIENTIFIC PERSONNEL SUPPORTED

The ARO MURI funding developed a large research infrastructure at UCLA. The research activities of six professors in the areas of Active Materials, Material Science, Mechanics, Rotorcraft Aeroelasticity, Experimental Fluid Mechanics, and MEMS were supported. More than 24 graduate students have received direct financial support on this grant with an additional 6 graduate students using the research infrastructure setup by the grant. In addition to graduate students, a number of undergraduate students participated on the program. Five postdoctoral scholars have been supported along with one technician. The following provides a list of support during the last two years.

Principal Investigators
Greg P. Carman
Bruce Dunn
Peretz Friedman
Tom Hahn
Chih-Ming Ho
CJ Kim

Engineers
Scott Keller

Postdocs
Quanfang Chen
Tom Barrera
Robert Cribbs
Seungbae Park
Milan Mitrovic

PhD students who earned degree on program
Chaplya, Paul
Park, Joon,
Fotinich, Eugene
Wang, Donny
Kurt Salloux
Taechung Yi
Timothy Myrtle
Marino deTerlizzi
Hani Alexander

MS students who earned degree on program

Keefe, Andrew
Lung-His, Chu
Zheng, Rong
Johal, Raman,
Roberts, Mark
Park, Sung
Van-Way, Craig
Brandon, Eby
Stam, Mike
Wayne Liu
Eric Prophet
Jimmy Lim
Poyi Huang
Jinghui Zhu
Lu Li

VI. TECHNOLOGY TRANSFER

A number of industries have expressed strong interest in our research program. To satisfy this interest and promote technology transfer, we formed an industrial advisory board (IAB) containing over 15 organizations. The IAB has met for four consecutive years (1996, 1997, 1998, and 1999) at UCLA following the SPIE Smart Structures and Materials conference in San Diego, California. Many of the companies are also providing financial and in-kind support to the UCLA research effort. Therefore, based on this strong involvement our program is viewed as highly successful by the industrial community. At this meeting the industries are provided access to our data and many use the results that we have generated in designing/building actuation systems for their applications. For example, the piezoelectric stack characterization is routinely requested by these and other industries. The following list provides an indication of companies involved with UCLA and potential technology transfer.

- Northrop Grumman ($140k in cash other in-kind support provided)
- Boeing ($270k cash)
- McDonnell Douglas ($50k in cash other in-kind support provided)
- Rockwell (over $50k in-kind material)
- Sikorsky (Cooperative Research Agreement signed)
- Aeroflightmechanics Lab Ames Research Center (yearly meetings)
- Sandia National Lab
- Channel (over $5k in-kind material)
- Xinetics (over $8k in-kind material)
- Memry Co (over $1k in-kind material)
- Etrema (over $40k + in-kind material)
- Satcon ($150k in cash support)
- MTS ($75k in-kind equipment)
- Micron ($5k in-kind support)
- Orbital Research ($50k in cash)
- Lawrence Livermore National Lab ($40k in cash)
- Piezokinetics/DARPA STTR ($50k in cash)

- Structures and Materials/DARPA STTR ($35k in cash)
- Burleigh/DARPA CHAP program ($281k in cash)
- IBM ($50k in-kind equipment)
- Lockheed
- Naval Research Lab
- others